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SOME PROPERTIES OF AN INJECTION-LOCKED
PULSED MAGNETRON

Peter A. DeVito

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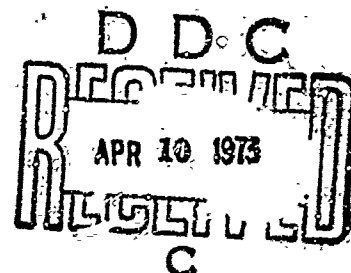


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Some Properties of an Injection-Locked Pulsed Magnetron

PETER A. DEVITO, MAJ, USAF



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A 22151

AD 758198

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY (Corporate author) Air force Cambridge Research Laboratories (AFSC) Microwave Physics Laboratory L.G. Hanscom Field, Bedford, Massachusetts 01730		2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP
3. REPORT TITLE SOME PROPERTIES OF AN INJECTION-LOCKED PULSED MAGNETRON		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Scientific. Interim.		
5. AUTHOR(S) (First name, middle initial, last name) Peter A. DeVito, Maj, USAF		
6. REPORT DATE 16 January 1973	7a. TOTAL NO. OF PAGES 26	7b. NO. OF REFS 17
8a. CONTRACT OR GRANT NO. LDF	9a. ORIGINATOR'S REPORT NUMBER(S) AFCRL-TR-73-0073	
a. PROJECT, TASK, WORK UNIT NOS. IL1R0001	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) PSRP No. 530	
c. DOD ELEMENT 681300		
d. DOD SUBELEMENT 61101F		
10. DISTRIBUTION STATEMENT Approved for public release; distribution unlimited.		
11. SUPPLEMENTARY NOTES This research was supported by the Air Force In-House Laboratory Independent Research Fund		12. SPONSORING MILITARY ACTIVITY Air Force Cambridge Research Laboratories (AFSC) Microwave Physics Laboratory L.G. Hanscom Field Bedford, Massachusetts 01730
13. ABSTRACT This paper describes injection-locking of positive-pulse microwave magnetrons by a stabilized low power source. A coherent echo-detection system utilizing an acoustic delay medium to simulate radar pulse return is employed to study phase coherence of injection-locked positive-pulsed magnetrons. Pulse-to-pulse coherence at ≈ 9 GHz is observed for extremely low input powers; the maximum output to input ratio—for which such locking is observed—is about 10^4 . This represents an improvement of 10% in the state-of-the-art. In addition, long term stabilities of better than one part in 10^5 /hr have been determined. Injection-locking has had limited application to microwave magnetron oscillators because of the relatively large amount of input power required. The technique consists of injecting output power from a low power oscillator into the interaction circuit of a second higher power oscillator. When the two output frequencies become sufficiently close, the higher power device locks or synchronizes to the lower power device and a single output frequency results. Phase pattern control of the RF output of an injection-locked pulsed magnetron is observed at 9.3 GHz. Phase coherence of the phase-coded output pulse is observed at an output-to-input power ratio of 40 dB. An almost phase-locked pulsed magnetron is used to demonstrate the occurrence of the Lashinsky Spectrum in RF oscillators. A nearly perfect textbook example of this asymmetric spectrum containing simultaneous amplitude and frequency modulation is obtained. Further development could lead to renewed interest in magnetrons in the field of coherent radar; for example, pulse doppler radar and moving target indication (MTI) radar. At the higher microwave frequencies—where the amplifier device makes up the larger portion of the weight and volume of the coherent radar system—the existence of a small, lightweight, efficient magnetron capable of being injection-locked would represent an advance in the coherent radar state-of-the-art.		

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Unclassified
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Security Classification

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AFCRL-TR-73-0073
16 JANUARY 1973
PHYSICAL SCIENCES RESEARCH PAPERS, NO. 530

MICROWAVE PHYSICS LABORATORY PROJECT ILIR

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**Some Properties of an Injection-Locked
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Some Properties of an Injection-Locked Pulsed Magnetron

1. INTRODUCTION

It is well known that a microwave oscillator can be locked in frequency and phase, to an externally-injected microwave signal having considerably smaller amplitude than the oscillator output signal. Practical injection-power levels required to produce locking in a pulsed magnetron, however, have been rather large; injection ratios as low as 10 to 20 dB appear to be common.

We have demonstrated that a magnetron can be locked in frequency and phase - with pulse-to-pulse coherence—to an external oscillator having an injection power 40 db below the magnetron output power. This input-output power ratio is 20 db higher than ratios previously attained in injection-locked magnetron systems.

This development could lead to a reappraisal of the magnetron as a radar power source. The magnetron, which was once the key component in radar systems, has seen decreasing use since the introduction of the klystron in the early 1950's. Injection-locked magnetrons of the type demonstrated at AFCRL could, however, offer several advantages over the klystron's lightweight, power efficiency, and possibly improved moving-target-indication (MTI) performance because of high frequency and phase stability.

Conventional pulsed-magnetron oscillators typically exhibit poor frequency stability and pulse-to-pulse coherence. A significant improvement in magnetron

(Received for publication 12 January 1973)

stability results from injection-locking with a relatively small signal. We have also discovered two new and important facets of injection-locked magnetrons. The first was a study in phase pattern control of the locked-magnetron output pulse. It was shown for the first time that the injection-locking technique can be used to generate and control varied phase patterns in the magnetron output pulse. An electronic phase-shifter produces a phase change in the injected signal and this phase change—via the injection-locking phenomenon—is reproduced in the magnetron output pulse, some 40 dB higher in power than the input pulse. In addition, pulse-to-pulse coherence is still preserved. It is demonstrated that by employing different phase shifting and gating sequences, elaborate coding schemes could be generated. The second study demonstrated the generation of a "Lashinsky Spectrum" in an almost phase locked magnetron. The "Spectrum" is unique in that it is asymmetric and contains simultaneous amplitude and frequency modulation.

These phenomena have strong impact in the use of injection-locked magnetrons for systems application. A coherent radar system employing an injection-locked magnetron with phase pattern control (pulse coding) would greatly reduce the system complexity coupled with improved range-resolution, reduced clutter, and lessen the radar's vulnerability to jamming. In addition there is application in coherent missile transponders, beacons and IFF.

2. INJECTION-LOCKED PULSED MAGNETRONS

A coherent echo-detection system utilizing an acoustic delay medium to simulate radar pulse return is employed to study phase coherence of injection-locked pulsed magnetrons. Coherence is defined when the phase of the transmitter pulse (magnetron pulse) is preserved in the reference signal (injection signal). Pulse-to-pulse coherence at ≈ 9 GHz is observed for extremely low input powers: the maximum output-to-input power ratio for which locking is observed is about 10^4 . This represents an improvement of 10^2 in the state-of-the-art.

The technique of injection-locking consists of injecting output power from a low power oscillator into the interaction circuit of a second higher power oscillator. When the two output frequencies become sufficiently close, the higher power device locks or synchronizes to the lower power device and a single output frequency is produced.

Injection-locking experiments were conducted at ≈ 9.3 GHz with the following parameters: magnetron pulse width = $1 \mu\text{sec}$, pulse repetition frequency = 1000 Hz and the magnetron peak output power = 250 W, nominal. A Microwave Associates grounded cathode positive-pulse magnetron (MA-249) was used.

The essential elements of the coherent X-band network employed in the injection-locking studies, initiated by Seavey (1967), is shown in the block diagram of Figure 1. This instrumentation is essentially an interferometer which may be used to measure velocity and absorption of sonic or ultrasonic waves in materials. The waves are transformed from RF energy by means of a CdS transducer or by the piezoelectric properties of the material, and the absorption or dispersion (velocity change) is determined by observing the phase and amplitude of the echoes.

In Figure 1, note that a CW reference signal passes through attenuator 1 and the phase shifter, and then is added to the echoes at the balanced mixer. Attenuator 1 is

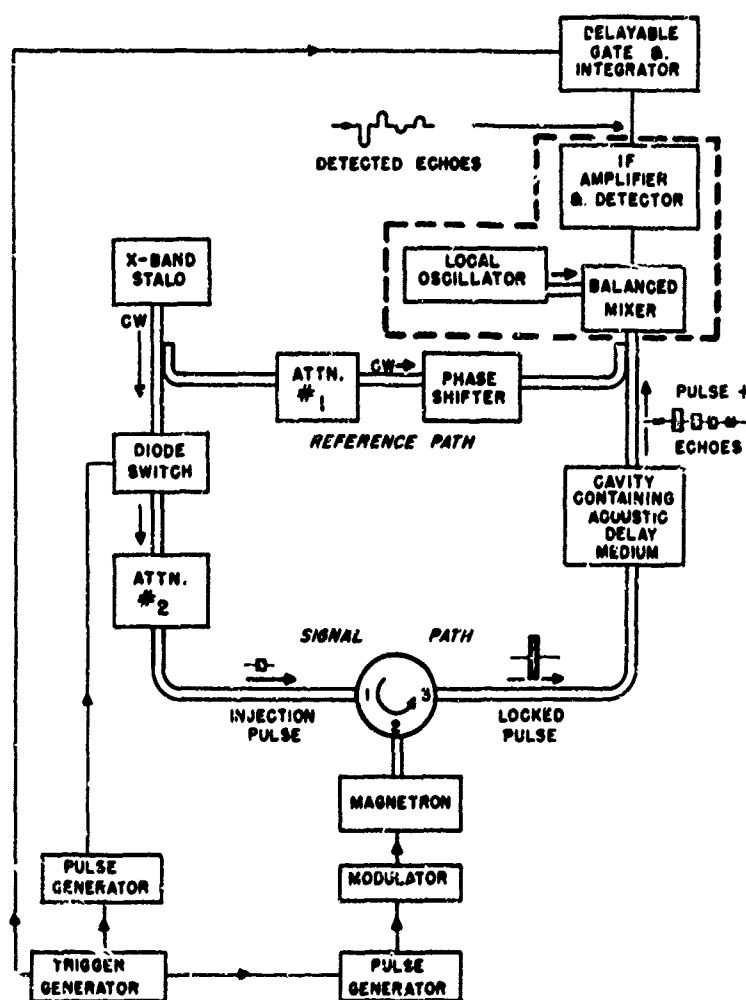


Figure 1. X-Band Interferometer Employing an Injection-Locked Magnetron

adjusted so that $V_R \gg V_S$ where V_R is the RF reference voltage and V_S is the RF signal voltage in an echo. The detected signal at the output of the video detector, assuming square-law detection, thus has an envelope amplitude of $2V_R V_S$. When the echo signals are coherently related to the CW reference signal, the detected signal becomes $2V_R V_S \cos \phi$, where ϕ is the phase angle between the reference signal and an echo signal. A typical coherently-detected echo pattern is indicated schematically in the upper part of Figure 1. Coherence is demonstrated if the detected echoes can be reversed in polarity by rotating the phase shifter.

Actual echo pulses generated by the acoustic-delay medium are shown in Figure 2. A coherently detected echo, indicating that the magnetron is completely locked, is shown in Figure 2(a). The phase angle between the detected echo signal and the CW reference signal is essentially 180° . This particular coherent echo is observed at 40 dB injection ratio (the injection ratio is the ratio of magnetron output power to injection input power expressed in dB). As the injection ratio is increased beyond approximately 40 dB, random echo traces occur superimposed on the main coherent trace [Figure 2(b)]. This represents the region of partial coherence, since some coherence can be demonstrated by rotating the phase shifter. Complete incoherence in this case [Figure 2(c)] does not occur until the injection ratio is greater than 46 dB.

The injection ratio is controlled by attenuator 2, as shown in Figure 1. Experimental values of normalized locking bandwidth as a function of injection ratio are plotted in Figure 3. The locking bandwidth is determined by adjusting the frequency tuner of the magnetron when it is phase-locked until a sudden change in power out of the cavity is observed on a crystal-diode monitor. Then enough attenuation is introduced to unlock the magnetron completely, and the frequency difference between the oscillators is read on a spectrum analyzer. The sudden change, or transient, begins on the trailing edge of the pulse and is caused by the initial loss of synchronization as the magnetron frequency is tuned away from the injection frequency. Such transients have been described theoretically for pulsed magnetrons by David (1952). The unlocking process is also monitored on the spectrum analyzer and is observed to occur at approximately the same tuner settings as for the onset of the transient.

The locking bandwidth is given by the expression (Adler, 1946)

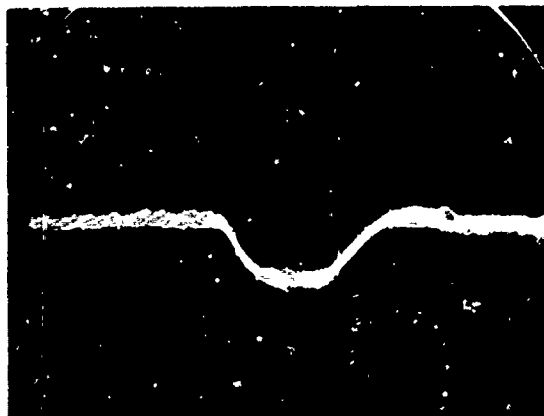
$$\Delta f = \frac{f_o}{2Q} \sqrt{\left(\frac{P_1}{P_o}\right)} \quad (1)$$

where

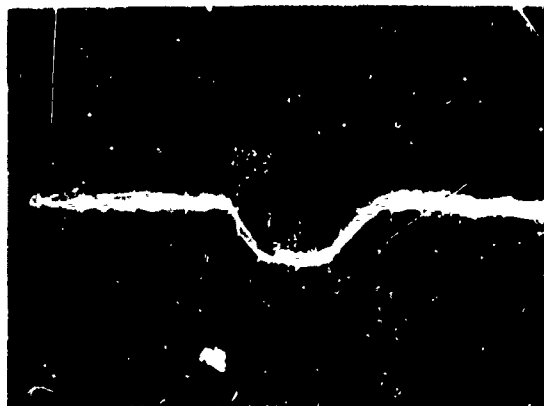
P_o = oscillator output power

P_1 = injection input power

(a)



(b)



(c)

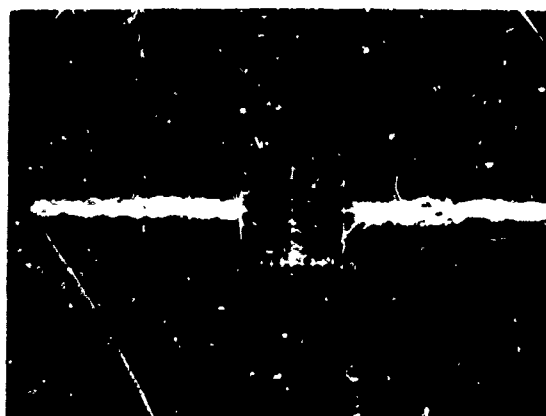


Figure 2. Detected Echoes Generated by Acoustic Delay Medium

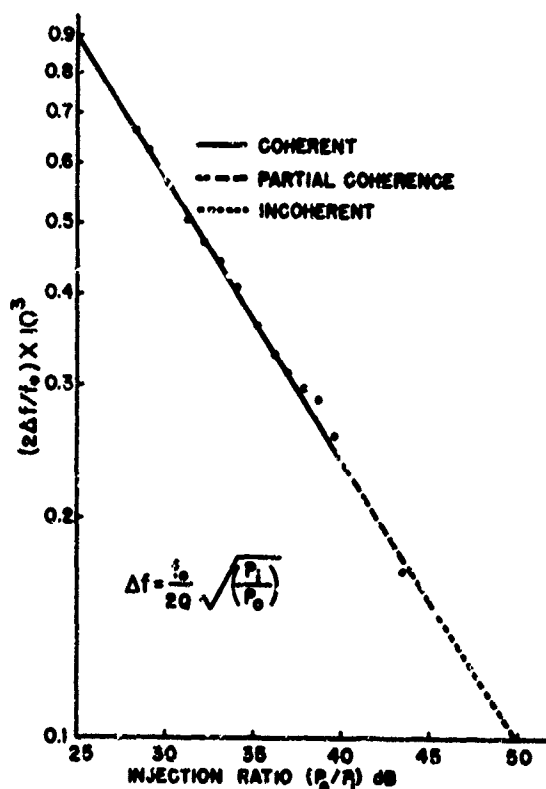


Figure 3. Normalized Locking Bandwidth vs Injection Ratio

$$\Delta f = f_0 - f_1$$

f_0 = free-running oscillator frequency

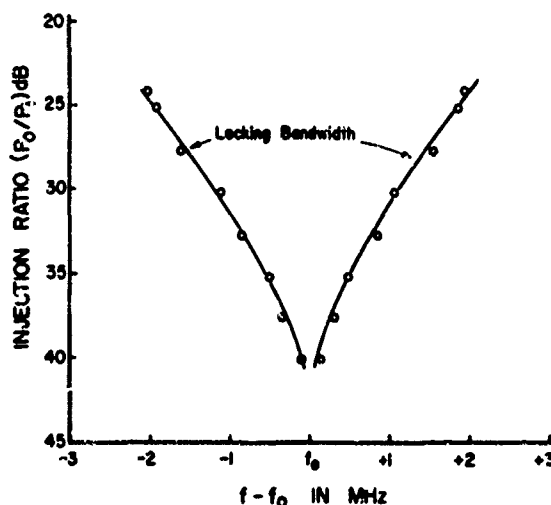
f_1 = injection input frequency

Q = figure of merit of loaded oscillator cavity

Agreement of the data of Figure 3 with this locking relation is only approximate. When substituted in Eq. (1), the data predict a monotonic decrease of Q from 58 to 37 as the injection ratio increases from 28 to 40 dB. This behavior is not at present understood, but it is probably related to the fact that the steady-state theory is not adequate to describe the pulsed case (David, 1952).

Figure 4 shows other experimental values of locking bandwidth as a function of injection ratio. In this particular experiment, complete incoherence did not occur until the injection ratio reached 52 dB. Variances in experimental data are attribute to parameter variables such as the pulse characteristics of the magnetron and injected signals, impedance of magnetron input-output port, and such inherent parameters associated with the specific magnetron.

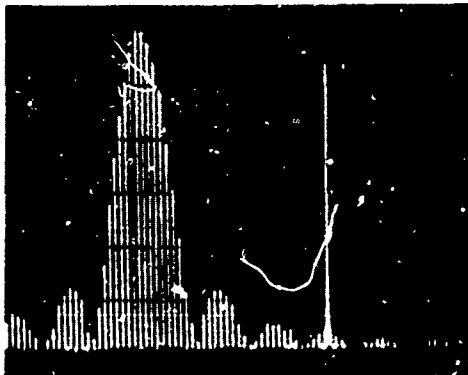
Figure 4. Lockbandwidth vs Injection Ratio



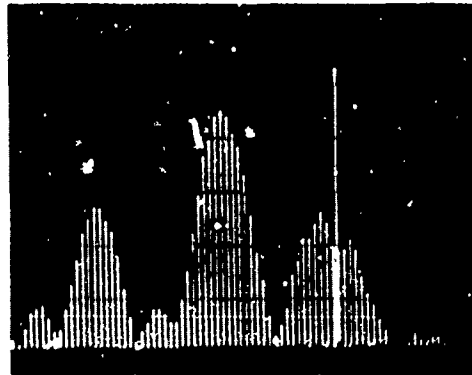
Spectral representation of the injection-locking phenomenon is depicted in Figures 5 and 6. In Figure 5(a), the Fourier spectrum of the magnetron is shown to the left of the injected pulse (shown as a CW signal on the spectrum analyzer). At this point the injected signal is outside the locking bandwidth of the magnetron. As the frequency of the injected pulse approaches that of the magnetron, the magnetron is "pulled" toward the locking signal [Figure 5(b)]. When the frequency of the injected signal is within the magnetron locking bandwidth, the magnetron "snaps" into the locked state [Figure 5(c)]. The next phenomenon to observe is the pulling effect of the injection-locked magnetron as shown in Figure 6. In the locked sequence [Figure 6 (a), (b), (c)] the injected signal frequency is varied within the locking bandwidth, thus "pulling" the magnetron with it. The output frequency of the magnetron during the pulling is, of course, equal to the frequency of the injected signal.

Coherence does not disappear immediately when the oscillators are unlocked by detuning. Instead, sharp frequency-modulation transients are superimposed on the echoes, and echo amplification is observed. For a 30 dB injection ratio during locking, the gain is about 25 dB just outside the locking range and falls to less than 10 dB for a frequency separation of about 8 MHz. This amplification phenomenon is probably characteristic of unlocked, but driven, oscillators and has been analyzed by Stover (1968) for CW oscillators.

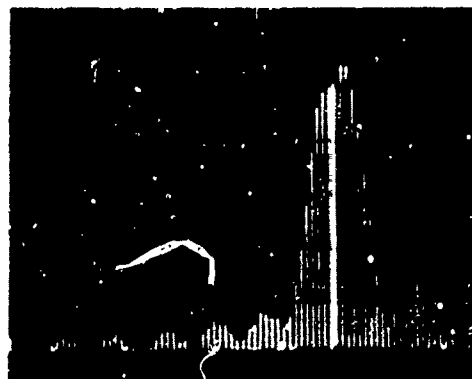
Frequency modulation across the top of the magnetron pulse (detuned condition) can be seen in the lower trace of Figure 7. Note that the injection pulse and magnetron pulse are in synchronization in the time domain. The duration of the



(a)

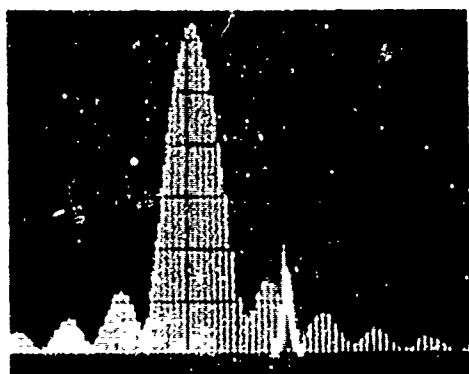


(b)

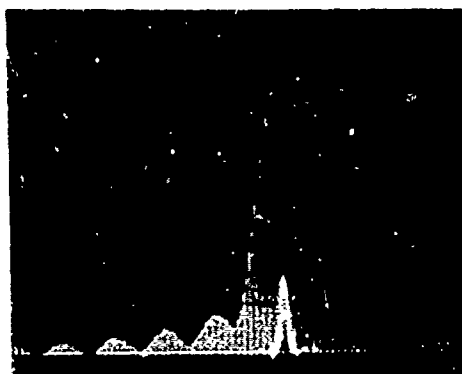


(c)

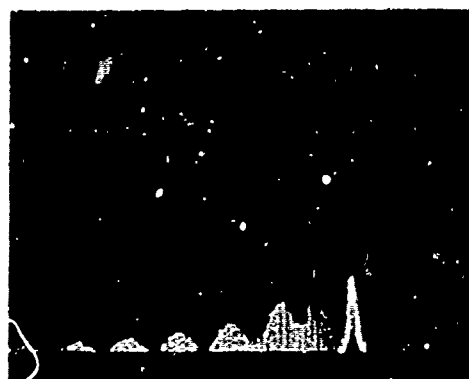
Figure 5. Spectrum of Positive-Pulse Magnetron Locking Sequence at ≈ 9300 MHz



UNLOCKED



LOCKED (a)



LOCKED (b)

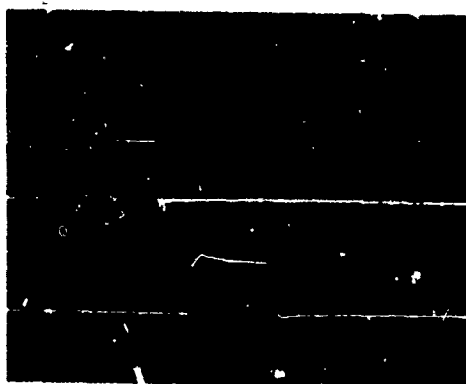


LOCKED (c)

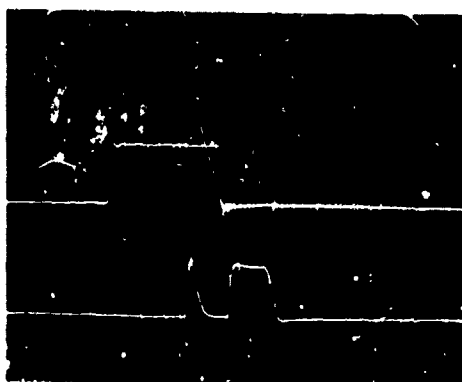
Figure 6. Pulling Effect of Injection-Locked Magnetron



Figure 7. Oscillograph of Injection Pulse (Upper Trace) and Detected Unlocked Magnetron Pulse After Reflection From the Resonant Cavity (Lower Trace) ($0.5 \mu\text{s}$ /horizontal division)



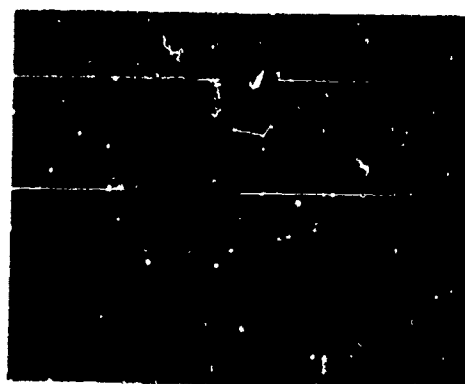
(a)



(b)



(c)



(d)

Figure 8. Oscillograph of Injection Pulse (Upper Trace) and Detected Magnetron Pulse After Reflection From the Resonant Cavity (Lower Trace) ($0.5 \mu\text{s}$ /horizontal division)

injected pulse starts before and ends after that of the magnetron pulse. For the unlocked case, see Figure 8(a).

As the width of the injection pulse is narrowed below the $1/\mu\text{sec}$ width of the magnetron output, the magnetron remains locked over that portion of its pulse covered by the injection pulse [see Figure 8(b)]—provided the latter pulse is "on" when the magnetron starts. For the remainder of the echo pulse, (the portion not covered by the injection pulse), the detected echo still appears "coherent"; that is, no superimposed random traces are observed. This latter effect is believed related to priming (described by Uhlir et al, 1966) and requires only that the magnetron start from the injected pulse. Figure 8(c) shows the completely locked case. No coherence is observed if the locking signal is injected into the magnetron after the magnetron pulse has started [Figure 8(d)] .

The reasons for the existence of the coherence at such high injection ratios are perhaps twofold. Firstly, the positive-anode construction of the magnetron appreciably reduces the preoscillation-noise generation. David (1952) has shown that a high injection-signal/preoscillation-noise ratio is a requirement for good pulse-to-pulse phase coherence. Secondly, the injection source has excellent short-term frequency stability (about 1 part in 10^6). A narrow-band injection signal should be expected to reduce the minimum-power level required for locking.

The system in Figure 1 is very suitable for long-term frequency-stability measurements. The time delay in the acoustic medium leads to the occurrence of large phase changes for small frequency variations. By setting the delayable gate on a particular echo and plotting the output of the integrator on an xy recorder, the phase change can be determined for any given time period (see Figure 1). The corresponding frequency change is calculated by using the acoustic-dispersion relation and the distance travelled by the acoustic pulse. Measurements are made both with and without the magnetron present, in order to compare magnetron and STALO stabilities. Results show that the stabilities are within a factor of two of each other for a 30 dB injection ratio.

The long-term frequency stability of the injection-locked magnetron indicates that the stability is essentially the same as that of the injected signal, in this case the STALO (less than 10 parts in 10^6 /hr).

The good stability properties may also make the system useful in an MTI radar. In fact, the scheme of Figure 1 is essentially the same as a particular one of the eight MTI schemes originally proposed in Ridenour (1947). To the best of the author's knowledge, Ridenour's MTI scheme has not found practical use because of the large amount of RF power normally required to lock a magnetron. In the present instance, however, the method appears practicable, at least for peak powers up to several hundred watts. Also, it is apparent that the stabilized output pulse would provide an excellent locking source for higher-power magnetrons.

3. PHASE PATTERN CONTROL OF INJECTION-LOCKED PULSED MAGNETRONS*

This section describes a unique method of generating and controlling varied phase patterns in a magnetron RF output pulse. Essentially, the technique consists of generating a phase pattern in the output pulses of a low-power stable oscillator (STALO) and injecting this low power signal with its distinctive phase characteristic, into the interaction circuit of a magnetron. It is shown for the first time that a positive pulsed magnetron, locked to a lower power oscillator, will transmit—at a considerably higher power (40 dB)—a pulse with the identical phase pattern as that of the injected signal. A Microwave Associates positive pulse beacon-type magnetron (MA-249) was used.

A simplified block diagram of the essential features of the instrumentation used is shown in Figure 9. A gated electronic phase shifter generates a pre-determined phase pattern in the pulsed low-power STALO injection signal. If the

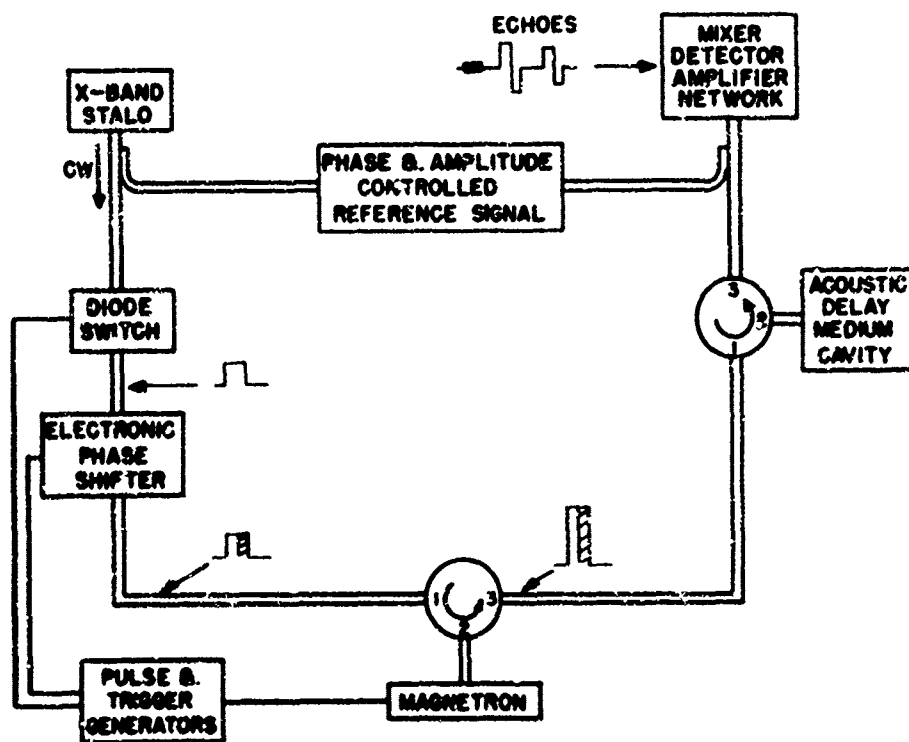


Figure 9. Block Diagram of Coherent X-Band System Employing Phase-Controlled Injection-Locked Magnetron

* See references for DeVito et al (1969) and DeVito, 1972.

frequencies of the magnetron and the STALO are sufficiently close, that is, within the locking bandwidth, the magnetron will synchronize or lock to the injection source. The locked magnetron in turn transmits pulses with the same phase pattern as the injected signal. Phase coherence on a pulse-to-pulse and intra-pulse to intra-pulse basis is observed for injection ratios as high as 40 dB. Phase coherence is established by the injection-locking mechanism in the pulsed magnetron.

A schematic representation of the phase patterns of the low power injection signal together with the detected echo, produced by the magnetron RF output, is shown in Figures 10 and 11. The detected signal, assuming square-law detection, has an envelope amplitude of $2V_R V_S$, where V_R is the RF reference voltage and V_S is the RF signal voltage in an echo. When the echo signals are coherently related to the CW reference signal, the detected signal becomes $2V_R V_S \cos \phi$, where ϕ is the phase angle between the reference signal and an echo signal.

In Figure 10(a), the injection signal pulse has a zero degree phase shift. In Figure 10(b), the phase of the entire injection pulse is changed 180° ; in turn, the higher power output pulse of the magnetron—in this particular case—instantaneously changes phase by 180° . This is verified by the 180° phase shift in the echo return. By sequential gating of the electronic phase shifter, alternate pulses can be made 180° out of phase or any combinatorial phase scheme can be produced within the pulse train. Since a 180° phase shift represents an extreme case imposed upon the magnetron, intuitively an infinite number of phase patterns between 0° and 180° can be attained by employing different phase shifters and gating sequences.

To produce more sophisticated phase patterns, phase changes within the pulse itself are employed. In Figure 11(a), the phase of the injection signal is changed midway between the rise and fall of each $1 \mu\text{sec}$ pulse. The locked magnetron, in turn, transmits a pulse with the same pattern as the injection signal as substantiated by the detected echo. Rise-time limitations in the mixer-detector-amplifier network account for the relatively smaller slopes in the detected echo pulse. Switching time of the phase change within the transmitted magnetron pulse was measured to be less than 100 nsec. We believe that the shortest switching time possible in this configuration is determined by the electronic phase shifter which has a rise time of less than 10 nsec. Figure 11(b) shows two 180° phase shifts between the second and last third of the pulse. Thus, by increasing the width of the transmitted pulse and by having a number of 180° phase changes, say 6 to 10, a phase digital-coded pulse would be produced within each pulse. Again, by employing different phase shifters and gating sequences, elaborate coding schemes could be generated.

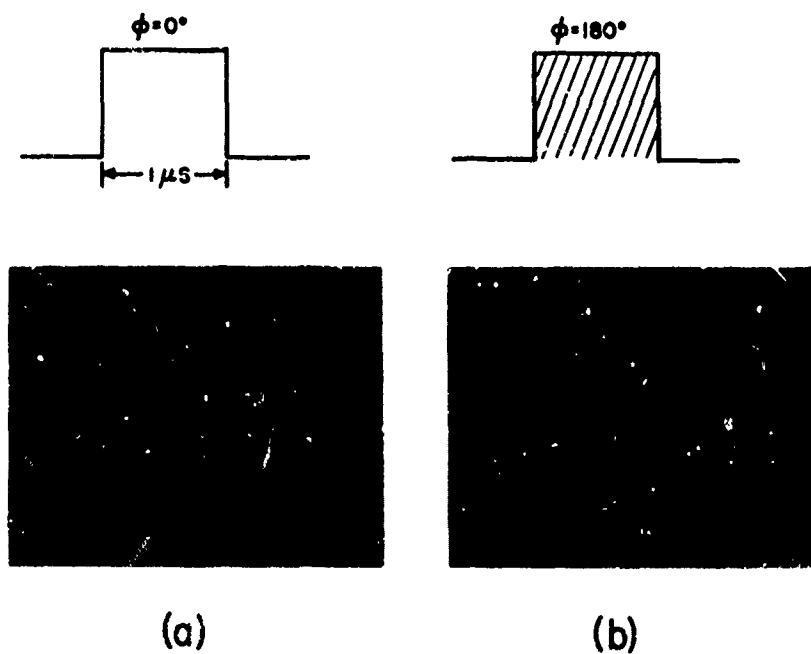


Figure 10. Schematic Representation of Injection Pulse (Top) and Detected Echo (Bottom)

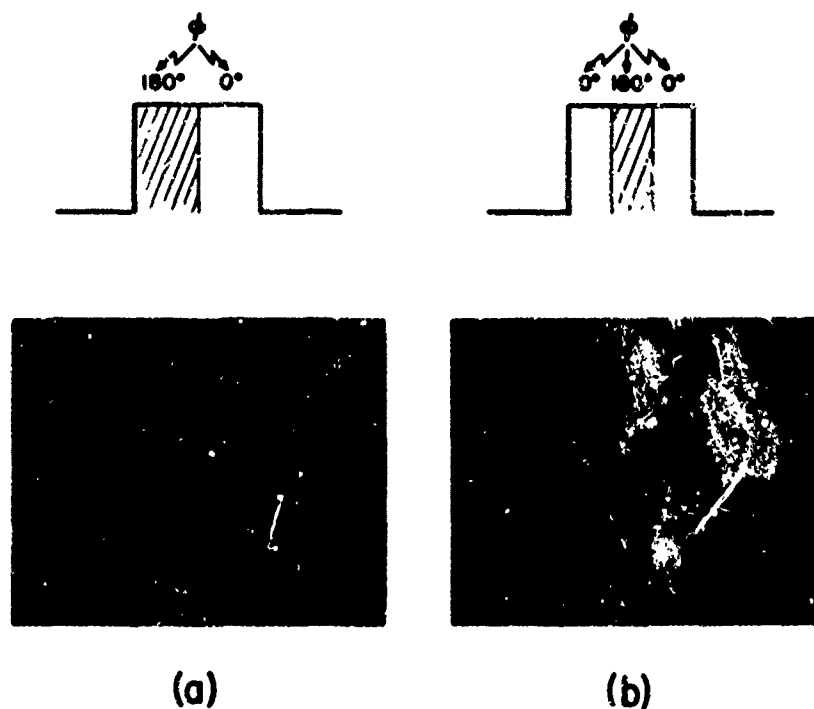


Figure 11. Schematic Representation of Phase Pattern of Injection Pulse (Top) and Detected Echo (Bottom)

4. THE ALMOST PHASE-LOCKED MAGNETRON AND THE LASHINSKY SPECTRUM*

There is a certain aperiodic effect which occurs just outside the "detuning range" or "locking bandwidth", which will form the basis of the discussion to follow.

The first mathematical treatment of entrainment (which, incidentally, includes phase-locking) was given by van der Pol (1927). In that treatment, the following Eq. (2) was derived from an equivalent circuit of a self-sustained oscillator with its characteristic approximated by a polynomial:

$$\ddot{X} + \mu(X^2 - 1)\dot{X} + X = E \sin \omega t \quad (2)$$

where X represents the voltage output of the oscillator, μ refers to the "strength of the nonlinearity", and the term on the right side represents the externally injected driving signal.

It was shown by van der Pol (1927) that the following conditions will give a solution which contains only the frequency of the external signal and does not contain the oscillator's own free-running frequency:

$$Z^2 > (1/2)a_0^2 \quad (3a)$$

$$a^2(1 - 3b^2/a_0^2)(1 - b^2/a_0^2) + Z^2 > 0 \quad (3b)$$

where a relates to the shape of the nonlinear characteristic. Let b designate the amplitude of the oscillator's response to the external signal, Z the detuning parameter (proportional to the difference between the limit cycle frequency and the injected frequency), and a_0 the amplitude of the free-running limit cycle (see van der Pol, 1927, for details). It can be shown (Dewan and Lashinsky, 1969) that condition Eq. (3a) is the condition for a form of entrainment known as "asynchronous quenching" which can occur only at values of Z that are away from the resonance region, and condition Eq. (3b) relates specifically to the "phase-locking" of the self-sustained oscillation.

When Z passes through the point where the inequality Eq. (3b) becomes an equality, one passes out of the locking bandwidth. In a region just outside this bandwidth, there is an interaction between the external input and the self-generated oscillations. This interaction is familiar to any TV viewer who has watched the jerking motion of the picture whenever one of the set's sweep generators has become desynchronized with respect to the transmitter. A mathematical description

* See references for Dewan and DeVito, 1970.

of this can be found in Hayashi (1964), and an approximate but physically insightful treatment can be found in Adler (1946).

The first investigator to observe this effect was Lord Rayleigh (1964) who saw the irregular relative phase variations in coupled tuning forks. His description was: "At one part of the cycle (of the beat) the changes are very slow and at the opposite part relatively quick." Adler's physical model involves a pendulum (whose position designates relative phase) which swings all the way around its pivot—going slowly around the inverted "unstable" point and rapidly through the stable equilibrium point. This phenomenon has been called "periodic pulling" or "snapping beats".

Lashinsky (1968) made a theoretical study of the spectrum of an oscillator during periodic pulling. His conclusion was that this spectrum (in contrast to the single line locked spectrum or the two lined non-interaction spectrum far outside the detuning range) shows the dispersion of energy over many frequencies on one side of a natural frequency. This "single sideband" spectrum contains simultaneous amplitude and frequency modulation effects, and is spread out from the natural frequency in the direction opposite to the side of the injected frequency. He showed, further, that the logarithm of the amplitude spectrum is a linear function of the frequency.

The question therefore arises: "Does one observe this Lashinsky Spectrum in microwave oscillators just outside the phase-locking zone?" Figure 12 shows the spectrum of the transmitted RF signal from an almost phase-locked pulsed magnetron. The frequency of the injected pulse is shown as a line spectrum at the right, just outside the detuning region. As can be seen, this has resulted in an almost perfect example of this type of spectrum.

Technical details of the experiment conducted by DeVito et al (1968) are as follows: The magnetron frequency was at about 9.3 GHz, magnetron pulse width = 1 μ sec, pulse repetition frequency = 1,000 Hz, and magnetron peak output power = 250 W nominal. A grounded cathode positive-pulse magnetron (MA-249) was used. Injection power was obtained by pulsing the CW output of an X-band stable oscillator (STALO).

It should be mentioned that periodic pulling and the spectrum associated with it can, in principle, be seen in any system involving the locking of self-sustained oscillations. For example, Lashinsky himself (Abrams et al, 1968) has observed it in RF excited plasmas. "Period pulling" has been directly seen in biological rhythms such as the motion of the fins of fish (Sollberger, 1965) (called relative coordination) and in almost phase-locked circadian rhythms (Aschoff, 1965). "Period pulling" should be observable in many electronic systems and possibly in various parts of physics now that it is easy to recognize it by means of its spectrum. In short, "period pulling" is an extremely general phenomenon, the knowledge of which might have practical importance in any field involving oscillations.

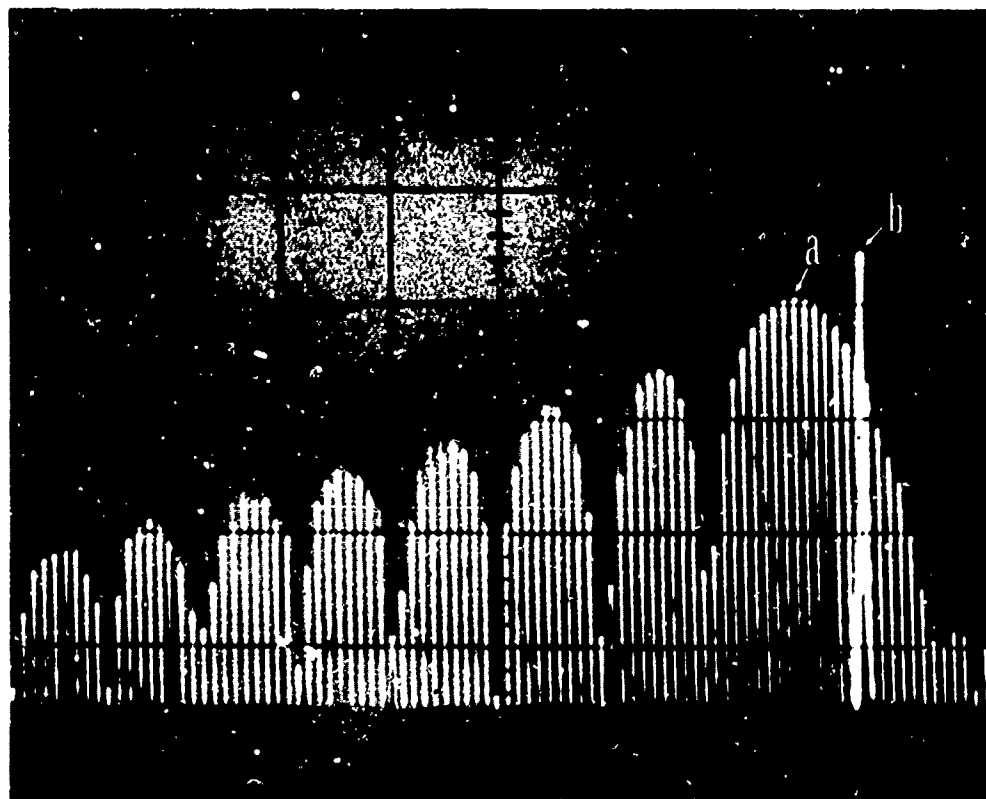


Figure 12. Spectrum of Magnetron Pulse (Logarithm of Amplitude vs Frequency) Showing the Characteristic Lashinsky Spectrum During Periodic Pulling. (a) Free-running magnetron frequency; (b) Injected frequency. Spectrum analyzer set for log vertical display and 1 MHz/cm on the horizontal axis

Further development in the phenomena described in this report could lead to renewed interest in injection-locked magnetrons for possible application in pulse coherent transponders, such as those used in missile systems, pulse doppler radar and moving target indication (MTI) radar. At the higher microwave frequencies, where the amplifier device makes up the larger portion of such systems, the existence of a relatively small, lightweight and high efficiency magnetron capable of being phase coded injection-locked would represent a significant achievement in the state-of-the-art.

Acknowledgments

M. H. Seavey, Jr. 's initial work in injection-locking provided the motivation for this study. We wish to thank E. M. Dewan for his theoretical work on the Lashinsky Spectrum and W. J. Kearns for his technical assistance.

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